

Type Synthesis of 3-DOF Multi-Mode Translational/Spherical Parallel Mechanisms with Lockable Joints

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Type Synthesis of 3-DOF multi-mode translational/spherical parallel mechanisms with lockable joints[☆]

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ABSTRACT

A 3-DOF (degrees-of-freedom) multi-mode translational/spherical PM (parallel mechanism) with lockable joints is a novel reconfigurable PM. It has both 3-DOF spatial translational operation mode and 3-DOF spherical operation mode. This paper presents an approach to the type synthesis of translational/spherical PMs with lockable joints. Using the proposed approach, several 3-DOF translational/spherical PMs are obtained. It is found that these translational/spherical PMs do not encounter constraint singular configurations and self-motion of sub-chain of a leg during reconfiguration. The approach can also be used for synthesizing other classes of multi-mode PMs with lockable joints, multi-mode PMs with variable kinematic joints, partially decoupled PMs, and reconfigurable PMs with a reconfigurable platform.

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1. Introduction

To develop reconfigurable manufacturing systems with a short changeover time, multi-mode PMs (parallel mechanisms) (also PMs with multiple operation modes or disassembly-free reconfigurable PMs) have received much attention from researchers since 2007 [1–8]. Multi-mode PMs have the following characteristics: a) Fewer actuators are needed for the moving platform to realize at least two motion patterns; and b) Less time is needed in reconfiguring the PM since there is no need to disassemble the PM in the process of reconfiguration. During the past ten years, a number of multi-mode PMs have been proposed [1–8] and a systematic approach [4,8] has been developed for the design of multi-mode PMs that have no lockable joint¹. Fig. 1 shows a 3-DOF(degrees-of-freedom) multi-mode PM developed by the first author's team at Heriot-Watt University, which is called DIRECTOR (Disassembly-free REConfigurable parallel manipulaTOR). The DIRECTOR has two 3-DOF operation modes: Operation Mode 1 – PPR equivalent mode – in which the moving platform rotates about an axis parallel to Y-axis that translates along the O-YZ plane, and Operation Mode 2 – E equivalent mode – in which the moving platform undergoes planar motion or rotates about an axis parallel to X-axis that translates along the O-YZ plane. It is composed of two PRU legs and one PUU leg. Here and throughout this paper, R, P and U denote a revolute joint, prismatic joint and universal joint respectively. As pointed out in [8], multi-mode PMs without lockable joint must pass through constraint singular configurations when switching from one operation mode to another. Brakes and timing belts are used to ensure the DIRECTOR passes through the constraint singular configurations.

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¹ A lockable joint in this paper refers to a joint that can be locked by a physical stopper attached to the joint itself.

Nomenclature

A joint	Lockable revolute joint that is locked in all the operation modes except operation mode A a multi-mode PM (parallel mechanism)
B joint	Lockable revolute joint that is locked in all the operation modes except operation mode B of a multi-mode PM
m	Number of joints in a leg of a multi-mode PM
m_A	Number of joints in a leg of PMs with a mono-operation mode associated with mode A of a multi-mode PM
m_B	Number of joints in a leg of PMs with a mono-operation mode associated with mode B of a multi-mode PM
m_c	Number of non-lockable joints in a leg of a multi-mode PM
R joint	Revolute joint
\tilde{R} joint	R joints within the same leg are parallel
\check{R} joint	R joints within the same leg are parallel but are not parallel to the axes of the \tilde{R} joints
\tilde{R} joint	R joints within a PM meet at one point
R^u joint	R joints whose axes are parallel to the axes of R joints within the same leg and meets the intersection of the axes of the \tilde{R} joints with a multi-mode PM in a transition configuration
ζ	Wrench
ζ_0	Wrench of 0-pitch (constraint force)
ζ_∞	Wrench of ∞ -pitch (constraint couple)

In addition, the first author of this paper also proposed a reconfigurable 3-5R PM with a Bricard-linkage-based reconfigurable moving platform (Fig. 2), which was investigated in detail in [9]. The mechanism (Fig. 2(a)) is composed of three 5R legs connecting the Bricard-linkage-based reconfigurable moving platform to the base. In each leg, the axes of the intermediate three R joints (2, 3 and 4), have parallel axes. The axes of the first joints (1) in all the legs meet at one point. The axis of the fifth joint (5) in each leg is coaxial with the axis of one R joint (6) of the Bricard linkage. By locking one R joint of the Bricard-linkage-based reconfigurable moving platform at different positions, the relative locations of the fifth joints in all the legs may vary. This leads to that the moving platform can undergo several 3-DOF motion patterns including spatial translation (Fig. 2(b)), spherical motion (Fig. 2(c)), planar motion (along three different planes), zero-torsion motion and general 3-DOF motion. Fig. 2(d) shows a prototype of this mechanism built in 2010 [9]. The use of reconfigurable platform makes it possible for a PM to transit from one operation mode to another without passing through constraint singularities.

A systematic study has also been made on metamorphic mechanisms [11] and metamorphic PMs [10,12,13,16]. For example, metamorphic PMs have been proposed by using reconfigurable U joint [10,12] and the variable axis joints [13]. These PMs are in fact kinematically redundant PMs. To realize the mobility change, these PMs must go through configurations in which a sub-chain of a leg is in self-motion.

Meanwhile, reconfigurable PMs with lockable joints have been proposed [14–16]. In [17], a systematic method has been developed for the construction of single-loop mechanisms with two operation modes from two single-loop overconstrained mechanisms by sharing different number of common joints. However, no systematic method has been proposed for the type synthesis of multi-mode PMs with lockable joints for two specified motion patterns.

In this paper, the approach to the type synthesis of multi-mode PMs without lockable joints [4,8] and single-loop mechanisms with two operation modes [17] will be further developed for synthesizing multi-mode PMs with lockable joints. During reconfiguration, such multi-mode PMs may avoid both constraint singular configurations, which multi-mode PMs without lockable joints suffer [4,8], or self-motion of a sub-chain, which the metamorphic PMs using reconfigurable joints or variable-axis joints [12,13] encounter.

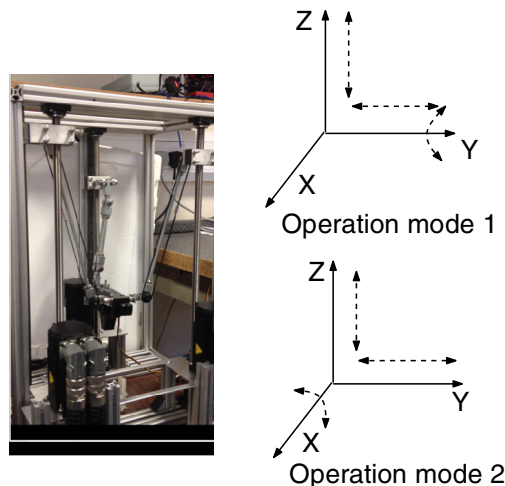


Fig. 1. DIRECTOR — a 3-DOF multi-mode PM.

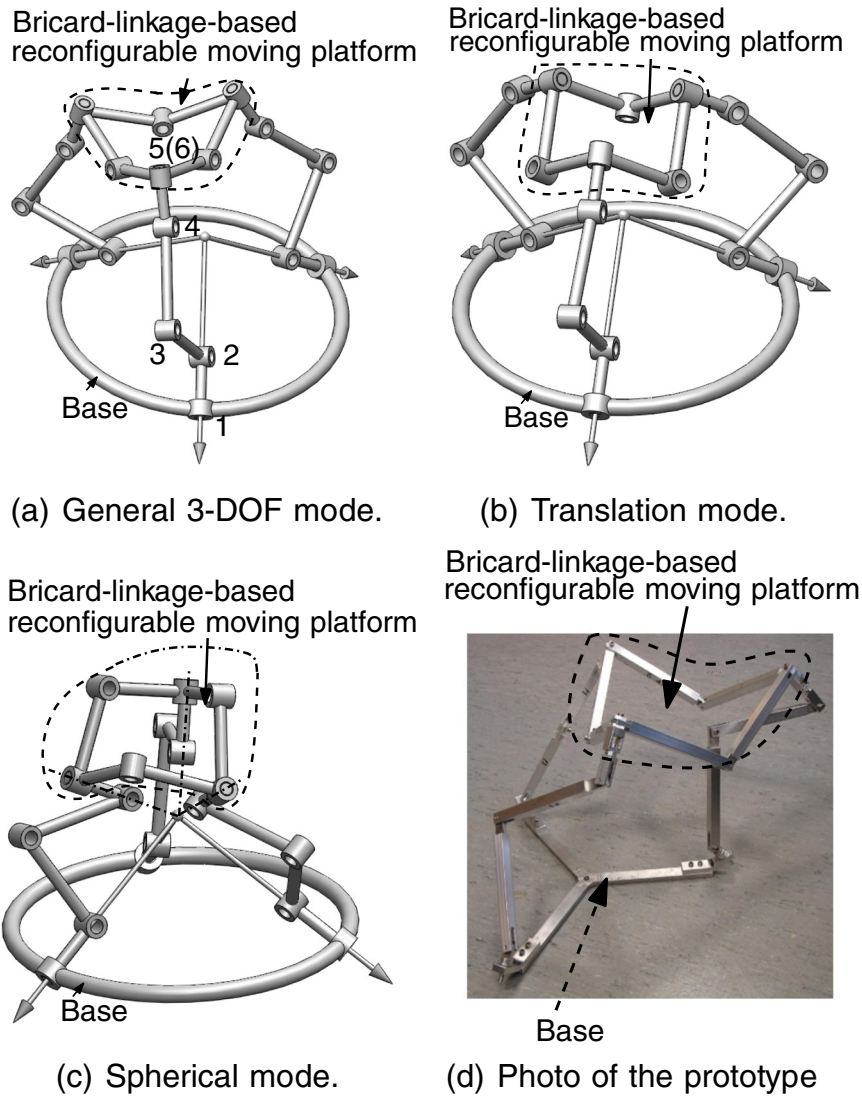


Fig. 2. A PM with a Bricard-linkage-based reconfigurable moving platform.

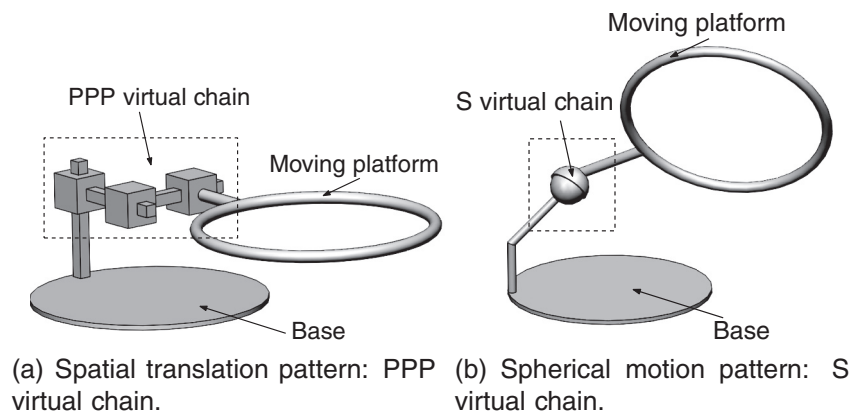


Fig. 3. Representation of motion patterns.

As it will be shown in Section 5, the approach can also be extended for synthesizing multi-mode PMs with variable kinematic joints, partially decoupled PMs, and reconfigurable PMs with a reconfigurable platform.

There are a large number of motion patterns and the classification of motion patterns is still an open issue. Considering that both the spatial translation motion (Fig. 3(a)) and spherical motion (Fig. 3(b)) are motion patterns in common use, this paper deals with the type synthesis of 3-DOF translational/spherical PMs – PMs with both 3-DOF spatial translational and 3-DOF spherical operation modes. Here, virtual chains [18] are used to represent the motion patterns vividly and unambiguously.

In Section 2, a method for the type synthesis of translational/spherical PMs with lockable joints will be proposed by extending the work in [4,8,17]. Using the proposed approach, the types of translational/spherical PMs will be obtained in Sections 3 and 4. Section 5 will discuss how to obtain multi-mode PMs with variable kinematic joints and partially decoupled PMs from the translational/spherical PMs with lockable joints. Finally, conclusions will be drawn.

In this paper, the following notations are used to denote the geometric relation among the joint axes of R joints for convenience. In a multi-mode PM at a transition configuration or a PM with a mono-operation mode, all the axes of \tilde{R} joints within the same leg are parallel, all the axes of \tilde{R}^v and \tilde{R} joints within the same leg are parallel, and the axes of \tilde{R} and \tilde{R}^v joints within the PM meet at one point—the center of spherical motion. In operation mode A (B) of a multi-mode PM, a lockable R joint that is not locked is denoted by A (B). In addition, ζ , ζ_0 and ζ_∞ are used to denote a wrench, a wrench of 0-pitch (constraint force) and a wrench of ∞ -pitch (constraint couple).

2. Approach to the type synthesis of translational/spherical PMs with lockable joints

In this section, an approach to the type synthesis of multi-mode PMs without lockable joint [4,8] and single-loop mechanisms with two operation modes [17] will be extended to the multi-mode PMs that have lockable joints.

Similar to the general procedure for the type synthesis of multi-mode PMs without lockable joints [4,8], the type synthesis of multi-mode PMs with lockable joints can be carried out using four steps:

Step 1: Type synthesis of legs for PMs with a mono-operation mode.

The type synthesis of PMs with a mono-operation mode, such as translational PMs and spherical PMs, has been well-documented in the literature (See [18] for example). For example, Fig. 4 shows an $\tilde{R}\tilde{R}\tilde{R}\tilde{R}\tilde{R}$ leg for 3-DOF translational PMs and an $\tilde{R}\tilde{R}\tilde{R}\tilde{R}\tilde{R}$ leg for 3-DOF spherical PMs, which will be used in the type synthesis of translational/spherical PMs with lockable joints in Section 3.

In the $\tilde{R}\tilde{R}\tilde{R}\tilde{R}\tilde{R}$ leg (Fig. 4(a)), the axes of the \tilde{R} joints are parallel, and the axes of the \tilde{R} joints are parallel but are not parallel to the axes of the \tilde{R} joints. The wrench system of the $\tilde{R}\tilde{R}\tilde{R}\tilde{R}\tilde{R}$ leg is a $1-\zeta_\infty$ -system in which the axis of the basis wrench $\zeta_{\infty 1}^i$ is perpendicular to all the axes of the \tilde{R} joints within the leg. In the $\tilde{R}\tilde{R}\tilde{R}\tilde{R}\tilde{R}$ leg (Fig. 4(b)), the axes of the \tilde{R} joints are parallel, and the axes of the \tilde{R} joints meet at the center of rotation of the moving platform. The wrench system of the $\tilde{R}\tilde{R}\tilde{R}\tilde{R}\tilde{R}$ leg is a $1-\zeta_0$ -system in which the axis of the basis wrench ζ_{01}^i passes through the intersection of the axes of the \tilde{R} joints and is parallel to all the axes of the \tilde{R} joints within the leg.

Step 2: Type synthesis of legs for multi-mode PMs with lockable joints.

Unlike translational/spherical PMs without lockable joints [4,8] in which each leg has five joints as the legs for each of the PMs with a mono-operation mode, a leg for translational/spherical PMs with lockable joints has six or more joints. In an operation mode of a multi-mode PM with lockable joints, the joints that do not belong to the associated PM with this mono-operation mode should be locked.

Details about this step will be discussed in Section 3.

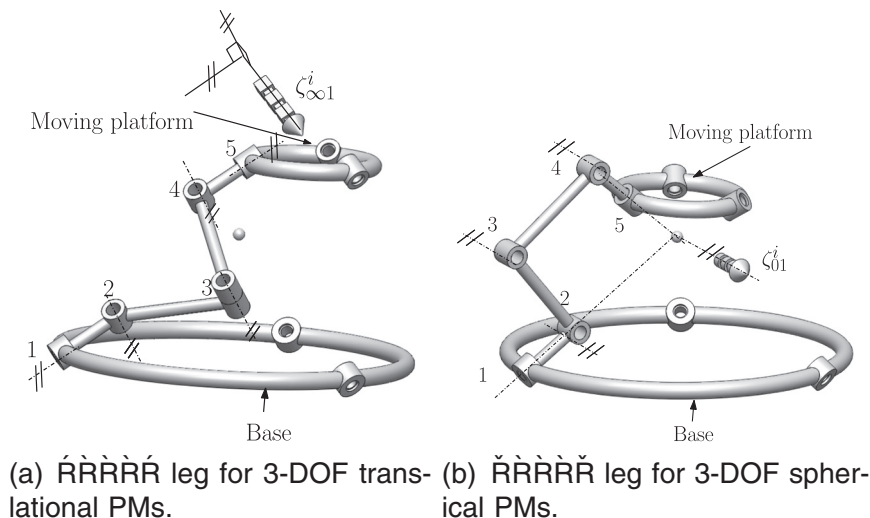


Fig. 4. Legs for PMs with a mono-operation mode.

Step 3: Assembly of legs for multi-mode PMs with lockable joints. In assembling a 3-DOF translational/spherical PM, it should satisfy both the assembly conditions for the translational PMs if the joints not associated with the 3-DOF spatial translation mode are locked and the assembly conditions for the spherical PMs [18] if the joints not associated with the 3-DOF spherical mode are locked.

Step 4: Selection of actuated joints for multi-mode PMs.

A set of f actuated joints for an f -DOF multi-mode PM with lockable joints is valid if it satisfies the validity condition of actuated joints [18] for each associated PM with mono-operation mode.

The above approach will be used to synthesize translational/spherical PMs in Sections 3 and 4. Since Steps 1 and 4 have been well-documented in the literature, Sections 3 and 4 will focus on Steps 2 and 3 respectively.

3. Step 2: type synthesis of legs for 3-DOF translational/spherical PMs with lockable joints

A leg for 3-DOF translational/spherical PMs with lockable joints has more joints than a leg for each of its associated PMs with mono-operation mode. A generalized procedure for Step 2: type synthesis of legs for 3-DOF translational/spherical PMs will be discussed in this section.

Let m and m_c denote, respectively, the number of joints and the number of non-lockable joints in a leg for multi-mode PMs. m_i ($i = A$ and B) represents the number of joints of a leg for PMs with a mono-operation mode associated with mode i of a multi-mode PM. We have

$$m = m_A + m_B - m_c.$$

Solving the above equation, m_c can be obtained for a given set of m_i and m as

$$m_c = m_A + m_B - m. \quad (1)$$

Since $m_c \leq \min(m_A, m_B)$, we have

$$m \geq \max(m_A, m_B). \quad (2)$$

In a leg for multi-mode PMs without lockable joint [4,8], we have

$$m = \max(m_A, m_B). \quad (3)$$

In a leg for multi-mode PMs with lockable joints, we have

$$m > \max(m_A, m_B). \quad (4)$$

In an m -joint leg for multi-mode PMs with lockable joints, one needs to lock $(m - m_A)$ lockable joints in operation mode A and $(m - m_B)$ lockable joints in operation mode B. Although there is no upper bound on m in theory, it is recommended to set

$$m \leq \min(m_A + m_B, 6). \quad (5)$$

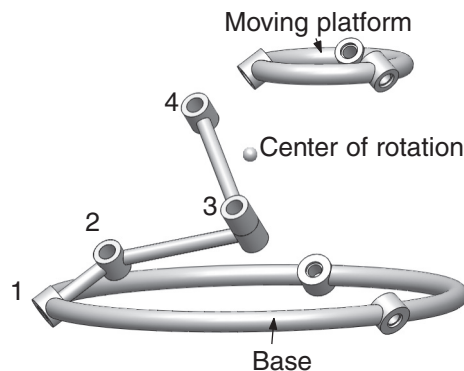


Fig. 5. Set of 4 non-lockable joints for legs for translational/spherical PMs: $\hat{R}^2\hat{R}\hat{R}\hat{R}$.

The case of $m > \min(m_A + m_B, 6)$ may lead to kinematically redundant PMs. Combining Eqs. (4) and (5), the range for the number of joints in a non-kinematically redundant leg for multi-mode PMs with lockable joints is obtained as

$$\max(m_A, m_B) < m \leq \min(m_A + m_B, 6). \quad (6)$$

By extending the work in [4,8,17], legs for multi-mode PMs with lockable joints, which satisfy Eq. (6) can be synthesized using the following steps.

- Step 2a For each value of m determined using Eq. (6), calculate m_c using Eq. (1).
- Step 2b For each value of m_c , select m_c non-lockable joints that satisfy the conditions for both legs of PMs with a mono-operation mode (see Fig. 4 for example). If there is no solution, go to Step 2e. Otherwise, go to next step.
- Step 2c For each set of m_c non-lockable joints obtained in Step 2b, insert $(m_A - m_c)$ lockable joints that together with the m_c non-lockable joints satisfy the conditions for legs for PMs with mono-operation mode A and $(m_B - m_c)$ lockable joints that together with the m_c non-lockable joints satisfy the conditions for legs for PMs with mono-operation mode B. If there is no solution, go to Step 2d. Otherwise, several legs for translational/spherical PMs have been obtained. Go to Step 2d.
- Step 2d Repeat Step 2c until all the sets of m_c non-lockable joints obtained in Step 2b have been considered.
- Step 2e Repeat Steps 2b–2d until all the values for m_c have been considered.
- Step 2f Repeat Steps 2a–2e until all the values for m have been considered.

In the remaining of this section, we will discuss how to obtain legs for 3-DOF translational/spherical PMs with lockable joints using the above procedure.

Here, we will illustrate the method by considering how to obtain legs for 3-DOF translational/spherical PMs from the $\check{R}\check{R}\check{R}\check{R}\check{R}$ leg for translational PMs (Fig. 4(a)) and $\check{R}\check{R}\check{R}\check{R}\check{R}$ leg for spherical PMs (Fig. 4(b)). In this case, we have $m_A = m_B = 5$. From Eq. (6), we have $m = 6$.

- Step 2a For $m = 6$, we obtain using Eq. (1) that $m_c = 4$.
- Step 2b Select $m_c = 4$ joints that satisfy the conditions for both legs of translational PMs and spherical PMs (Fig. 4). Three sets of 4 non-lockable joints, $\check{R}^v\check{R}\check{R}\check{R}$ (Fig. 5), $\check{R}^v\check{R}\check{R}\check{R}^v$ and $\check{R}\check{R}\check{R}\check{R}^v$, are obtained by comparing the conditions of the legs for PMs shown in Fig. 4. In the $\check{R}\check{R}\check{R}\check{R}\check{R}$ leg, the axes of the \check{R} joints are parallel, and the axis of the \check{R} joint passes through the center of rotation of the moving platform.
- Step 2c For each set of m_c non-lockable joints obtained in Step 2b, insert $1 (= m_A - m_c = 5 - 4)$ lockable joint, denoted by A, that together with the 4 non-lockable joints satisfy the conditions for legs for translational PMs and $1 (= m_B - m_c = 5 - 4)$ lockable joint, denoted by B, that together with the 4 non-lockable joints satisfy the conditions for legs for spherical PMs. In operation mode A (spatial translational mode) of the PM, joint A is not locked and joint B is. In operation mode B (spherical mode) of the PM, joint B is not locked and joint A is. From the $\check{R}^v\check{R}\check{R}\check{R}$ set of 4 non-lockable joints (Fig. 5), we can obtain four legs for translational/spherical PMs: the $\check{R}^v\check{R}\check{R}\check{R}\check{A}\check{B}$ leg (Fig. 6(a)), $\check{R}^v\check{R}\check{R}\check{R}\check{B}\check{A}$ (Fig. 6(b)), $\check{R}^v\check{B}\check{R}\check{R}\check{R}\check{A}$, and $\check{B}\check{R}^v\check{R}\check{R}\check{A}$. The wrench system of each leg is a 0- ζ -system if both \check{A} and \check{B} joints are not locked, a 1- ζ_∞ -system in which the axis of the basis ζ_∞ is perpendicular to all the axes of the \check{R} joints within the same leg if only the \check{B} joint is locked, a 1- ζ_0 -system if only the \check{A} joint is locked, or a 1- ζ_∞ -1- ζ_0 -system if both the \check{A} and \check{B} joints are locked.

Similarly, one can obtain four legs for translational/spherical PMs from the $\check{R}\check{R}\check{R}\check{R}^v$ set of 4 non-lockable joints. From the $\check{R}^v\check{R}\check{R}\check{R}^v$ set of 4 non-lockable joints, no leg with 6 joints for translational/spherical PMs is obtained since the legs obtained degenerate into the 5R legs in [4].

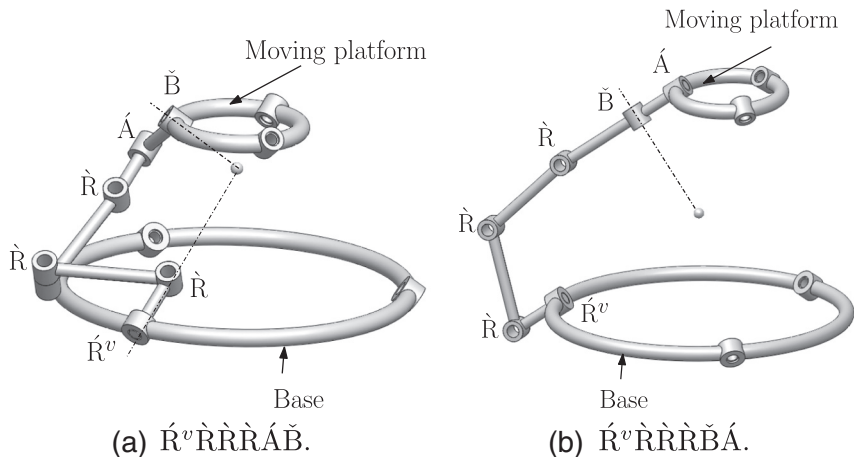


Fig. 6. Legs for translational/spherical PMs with lockable joints.

Table 1

Legs for multi-mode PMs with lockable joints.

c^i	Class	No	Type	Description
0	6R	1	$\hat{R}''\hat{R}\hat{R}\hat{A}\hat{B}$	The axes of \hat{R} joints within the same leg are parallel, the axes of \hat{R}' , \hat{R} and \hat{A} within the same leg are parallel but are not parallel to the axes of the \hat{R} joints, and the axes of \hat{R}' and \hat{B} within the mechanism meet at one point. Here, R denotes revolute joint while A and B denote lockable R joints. In operation mode A of a PM, joint A is not locked and joint B is. In operation mode B of a PM, joint B is not locked and joint A is.
		2	$\hat{R}''\hat{R}\hat{R}\hat{B}\hat{A}$	
		3	$\hat{R}'\hat{B}\hat{R}\hat{R}\hat{A}$	
		4	$\hat{B}\hat{R}'\hat{R}\hat{R}\hat{A}$	
		5	$\hat{A}\hat{R}\hat{R}\hat{R}'\hat{B}$	
		6	$\hat{A}\hat{R}\hat{R}\hat{R}\hat{B}'$	
		7	$\hat{A}\hat{B}\hat{R}\hat{R}\hat{R}'$	
		8	$\hat{B}\hat{A}\hat{R}\hat{R}\hat{R}'$	

Table 1 shows the eight types of legs for translational/spherical PMs obtained from the $\hat{R}''\hat{R}\hat{R}\hat{A}\hat{B}$ leg for translational PMs and all the legs for spherical PMs. For the sake of brevity, the types of legs for translational/spherical PMs associated with other types of legs for translational PMs are omitted here.

4. Step 3: assembly of 3-DOF translational/spherical PMs

In this section, we will discuss how to obtain 3-DOF translational/spherical PMs by assembling the legs obtained in Section 3.

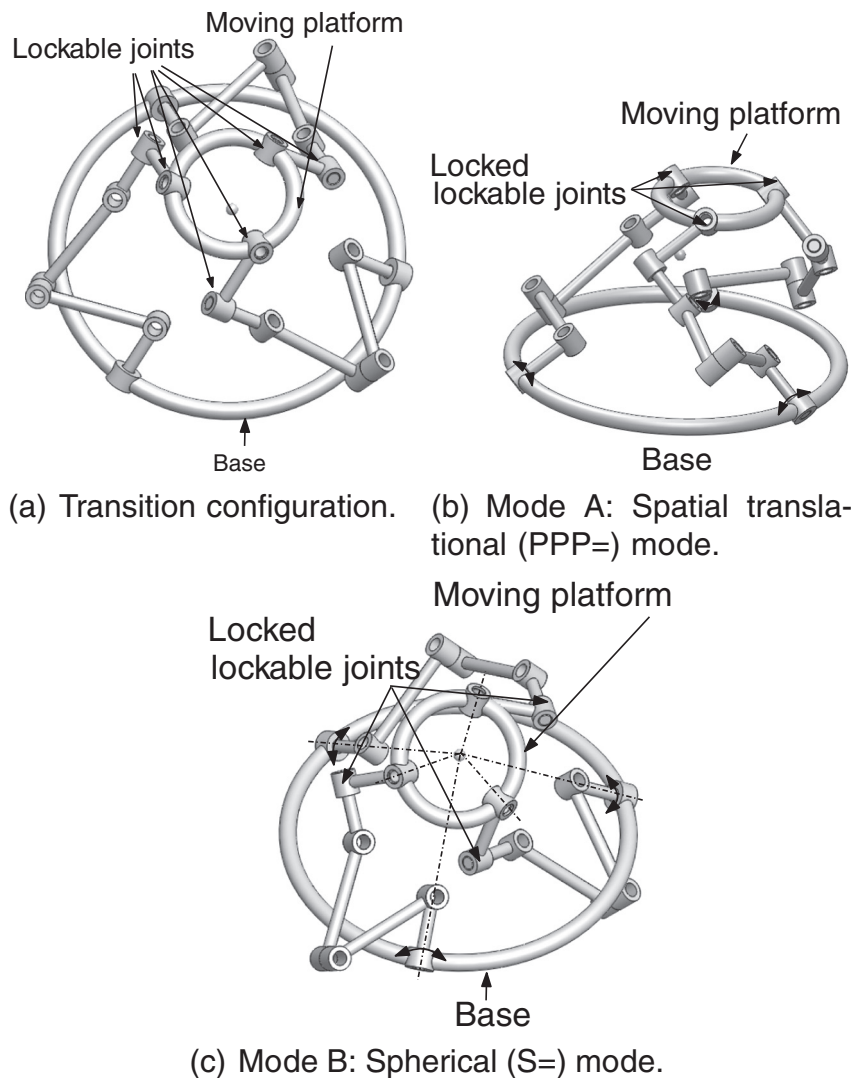


Fig. 7. 3-DOF $3-\hat{R}''\hat{R}\hat{R}\hat{A}\hat{B}$ translational/spherical PM with six lockable joints.

In assembling a 3-DOF translational/spherical PM, it should satisfy both the assembly conditions for the translational PMs if the joints not associated with the 3-DOF spatial translation mode are locked and the assembly conditions for the spherical PMs [18] if the joints not associated with the 3-DOF spherical mode are locked. To guarantee that the DOF of a translational/spherical PM is three and not greater than three at a regular configuration if the joints not associated with the corresponding operation mode are locked, the linear combination of all its leg-wrench systems should be a 3- ζ_0 -system if the PM works in the spherical mode or a 3- ζ_∞ -system if the PM works in the spatial translational mode. From the previous section, it is found that a leg for translational/spherical PMs has a 1- ζ -system in a regular configuration (Table 1), if either the \hat{A} or \hat{B} joint is locked. Since the leg-wrench system of each leg varies with the change of its configuration, we make the assumption that such conditions are met as long as a 3-DOF translational/spherical PM is composed of at least three legs listed in Table 1.

By assembling the legs listed in Table 1 and their variations, a large number of translational/spherical PMs can be obtained. The geometric constraints among legs of a PM can be clearly shown in a transition configuration of the PM by the notation of R joints: The axes of \hat{R}^v , \hat{R} and \hat{A} within the same leg are parallel, and the axes of \hat{R}^v and \hat{B} within the PM meet at one point. The sum of all the three leg-wrench systems is a 3- ζ_∞ -system if all the three \hat{B} joints are locked or a 3- ζ_0 -system if all the three \hat{A} joints are locked.

For example, one can obtain a 3- $\hat{R}^v\hat{R}\hat{R}\hat{A}\hat{B}$ PM (Fig. 7) by assembling three $\hat{R}^v\hat{R}\hat{R}\hat{A}\hat{B}$ legs (Fig. 6(a)). In the transition configuration of this PM (Fig. 7(a)), the axes of \hat{R}^v , \hat{R} and \hat{A} within the same leg are parallel, the axes of \hat{R}^v and \hat{B} within the PM meet at one point, and all the six \hat{A} and \hat{B} joints are locked. The DOF of the PM is 0.

Through this transition configuration, the PM can switch between the spatial translational mode (Fig. 7(b)) and the spherical mode (Fig. 7(c)). In the spatial translation mode (Fig. 7(b)), all the three \hat{B} joints are locked. Each $\hat{R}^v\hat{R}\hat{R}\hat{A}\hat{B}$ leg is reduced to an $\hat{R}^v\hat{R}\hat{R}\hat{A}$ leg that has two groups of R joints with parallel axes: a group of three \hat{R} joints and a group of \hat{R}^v and \hat{A} joints. The wrench system of each $\hat{R}^v\hat{R}\hat{R}\hat{A}$ leg is a 1- ζ_∞ -system in which the axis of the basis wrench ζ_{b1}^l is perpendicular to all the axes of the R joints within the same leg. The sum of all the three leg-wrench systems is a 3- ζ_∞ -system, and the moving platform can undergo 3-DOF spatial translation. In the spherical mode (Fig. 7(c)), all the three \hat{A} joints are locked. Each $\hat{R}^v\hat{R}\hat{R}\hat{A}\hat{B}$ leg is reduced to an $\hat{R}^v\hat{R}\hat{R}\hat{B}$ leg that has two groups of R joints: a group of three \hat{R} joints with parallel axes and a group of \hat{R}^v and \hat{B} joints with intersecting axes. The wrench system of each $\hat{R}^v\hat{R}\hat{R}\hat{B}$ leg is a 1- ζ_0 -system in which the axis of the basis wrench ζ_{b1}^l passes through the intersection of the axes of the \hat{R}^v and \hat{B} joints and is parallel to all the axes of the \hat{R} joints within the same leg. The sum of all the three leg-wrench systems is a 3- ζ_0 -system, and the moving platform can undergo 3-DOF spherical motion.

Since the 3- $\hat{R}^v\hat{R}\hat{R}\hat{A}\hat{B}$ PM is a translational PM in the translational operation mode or a spherical PM in the spherical mode (see [18] for example), the translational/spherical PM undergoes finite motion (or has full-cycle mobility) in each operation mode.

It can be verified using the procedure in [18,4] that the three \hat{R}^v joints can be selected as actuated joints to control the 3- $\hat{R}^v\hat{R}\hat{R}\hat{A}\hat{B}$ PM in both the translational mode and the spherical mode.

Unlike the PMs in [1–8] and [12,13], the 3- $\hat{R}^v\hat{R}\hat{R}\hat{A}\hat{B}$ translational/spherical PM does not encounter constraint singular configurations or self-motion of sub-chain of a leg during reconfiguration.

5. Discussion

In this section, we will discuss briefly how to extend the above method for the type synthesis of multi-mode PMs with lockable joints to the type synthesis of multi-mode PMs with variable kinematic joints, partially decoupled PMs, and reconfigurable PMs with a reconfigurable platform.

Firstly, the approach to the type synthesis of multi-mode PMs with lockable joints will be used to the type synthesis of multi-mode PMs with variable kinematic joints [19,21,20], such as variable R joint denoted by R_+ [21], whose axis of rotation may change. Fig. 8 shows an R_+ joint in the form of a simple kinematotropic linkage in which two links, Links a and b, are connected by a 4R mechanism 1–2–3–4. In the transition configuration (Fig. 8(a)), the axes of joints 1 (2) and 3 (4) are collinear. Links a and b have two instantaneous relative DOF. In the R_+ mode (Fig. 8(b)), the axes of joints 1 and 3 remain collinear, and joints 2 and 4 become inactive (or lose their DOF). Therefore Links a and b can only rotate about the axes of joints 1 and 3 with respect to each other. In the R_- mode (Fig. 8(c)), the axes of joints 2 and 4 remain collinear, and joints 1 and 3 become inactive. Therefore Links a and b can rotate about the axes of joints 2 and 4 with respect to each other.

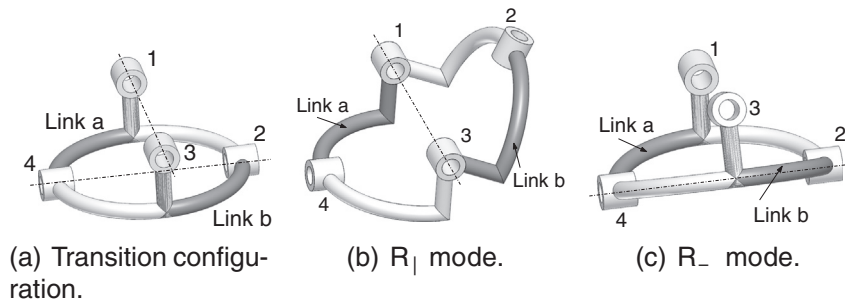


Fig. 8. R_+ joint in the form of a spatial 4R mechanism.

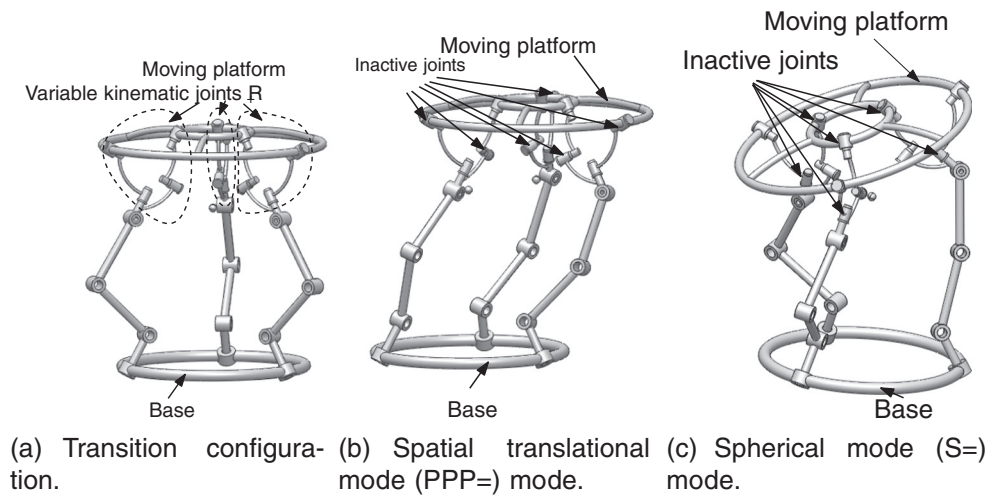


Fig. 9. 3-DOF translational/spherical PM with three R_+ joints.

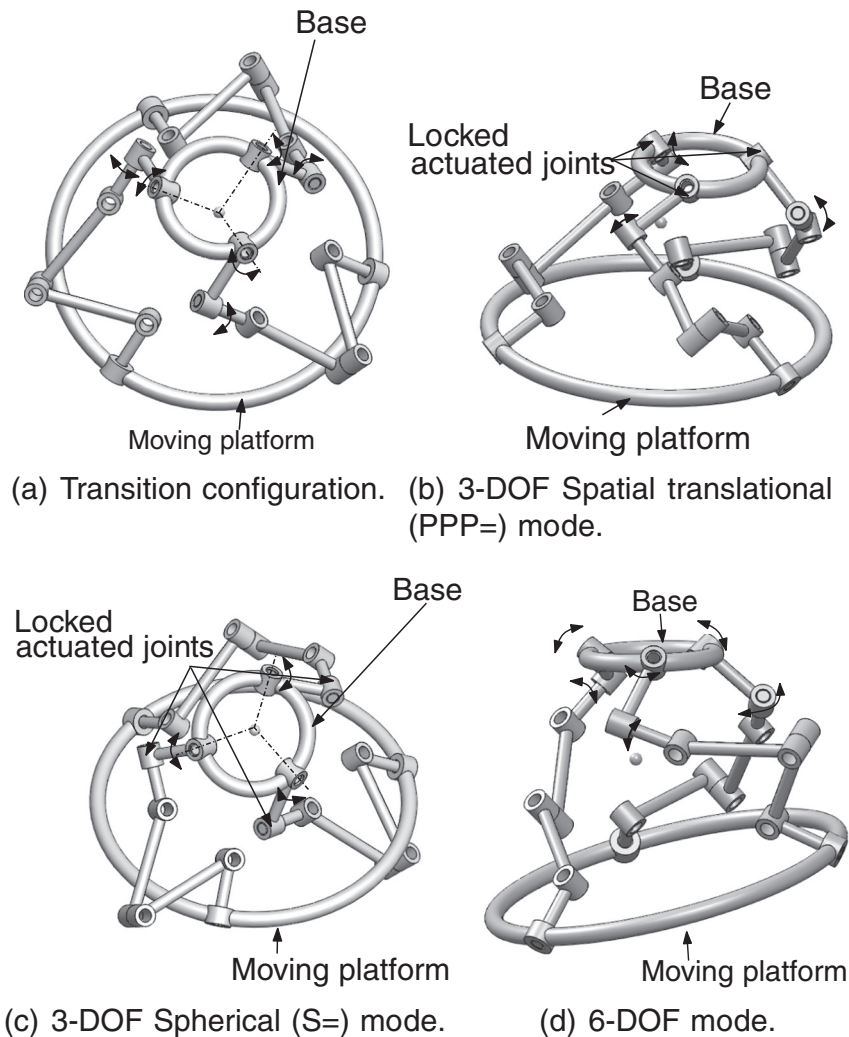


Fig. 10. 6-DOF 3-BARRRR partially decoupled PM.

For example, by replacing each combination of \hat{A} and \hat{B} joints in a 3-DOF $3-\hat{R}^v\hat{R}\hat{R}\hat{A}\hat{B}$ translational/spherical PM with an R_+ joint, we obtain a 3-DOF translational/spherical PM with three R_+ joints (Fig. 9). Here, each R_+ joint is composed of four R joints in which two R joints are along the axis of the \hat{A} joint and the remaining two R joints are along the axis of the \hat{B} joint in the transitional configuration (Fig. 9(a)). In each operational mode (such as the spatial translational mode shown in Fig. 9(b) and spherical mode shown in Fig. 9(c)), a pair of R joints within an R_+ joint become inactive.

Secondly, the approach to the type synthesis of multi-mode PMs with lockable joints can be used to the type synthesis of multi-mode PMs with a reconfigurable platform [9]. In the 3-DOF $3-\hat{R}^v\hat{R}\hat{R}\hat{A}\hat{B}$ translational/spherical PM with lockable joints (Fig. 7), six lockable joints are used. In order to reduce the number of lockable joints, a reconfigurable platform can be used. In the reconfigurable PMs with a reconfigurable platform shown in Fig. 2, the reconfigurable platform was obtained by designing a 1-DOF single-loop mechanism in which three R joints of the single-loop mechanism will be the three \hat{A} joints in one configuration to reach the 3-DOF spatial translational mode (Fig. 2(b)) and become the three \hat{B} joints in another configuration to reach the 3-DOF spherical mode (Fig. 2(c)). Therefore, only one lockable joint is needed in the translational/spherical PM with a reconfigurable platform shown in Fig. 2.

Finally, the approach to the type synthesis of multi-mode PMs with lockable joints can be used to the type synthesis of partially decoupled PMs [22] (also called group decoupled PMs [23,24]). For example, by replacing the \hat{A} and \hat{B} lockable joints in a 3-DOF $3-\hat{R}^v\hat{R}\hat{R}\hat{A}\hat{B}$ translational/spherical PM each with an actuated joint, we obtain a 6-DOF $3-\hat{B}\hat{A}\hat{R}\hat{R}\hat{R}^v$ partially decoupled PM (Fig. 10). By locking the three actuated \hat{B} joints in the transition configuration (Fig. 10(a)), the PM works as a 3-DOF translational PM (Fig. 10(b)). By locking the three actuated \hat{A} joints in the transition configuration, the PM works as a 3-DOF spherical PM (Fig. 10(c)). In the 6-DOF operation mode, the axes of the \hat{B} , \hat{A} and \hat{R}^v within a leg may not satisfy the geometric conditions, such as parallel axes and intersecting axes, any more (Fig. 10(d)).

It is noted that the partially decoupled PM shown in Fig. 10 has different characteristics from those in [22–24], which have prismatic joints and can switch between a 3-DOF operation mode and the 6-DOF mode in any configuration by locking/releasing three actuated joints. As pointed out in [25], the number of operation modes of a multi-mode PM may be larger than expected.

By uplifting the upper bound on the number of joints in a leg for multi-mode PMs through the use of Eq. (4) instead of Eq. (6), the approach presented in this paper can also be extended to the design of metamorphic PMs with reconfigurable joints or variable-axis joints [11–13] for generating two specified motion patterns.

6. Conclusions

An approach has been proposed to the type synthesis of 3-DOF translational/spherical PMs with lockable joints and several 3-DOF translational/spherical PMs with lockable joints have been presented. It has been found that these translational/spherical PMs do not encounter constraint singular configurations or self-motion of sub-chain of a leg during reconfiguration.

This work, together with [4,8], has established a systematic approach to the type synthesis of multi-mode PMs and thus lays a solid foundation for further research on these mechanisms for reconfigurable manufacturing systems and for the type synthesis of multi-mode PMs with variable kinematic joints, partially decoupled PMs, reconfigurable PMs with a reconfigurable platform, and other types of multi-mode PMs with lockable joints.

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